



40 Years of Electron Cooling at CERN

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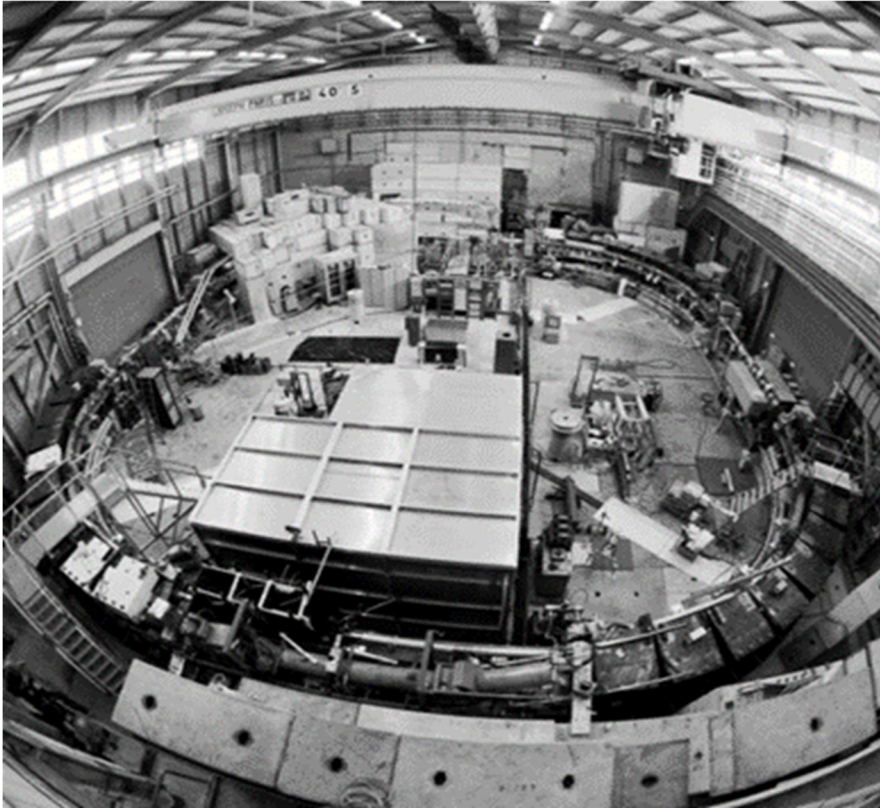
OUTLINE

- The ICE age - the birth of electron cooling at CERN
- LEAR – electron cooling in operation
- From LEAR to LEIR
- AD – cooling for antimatter
- ELENA and the future

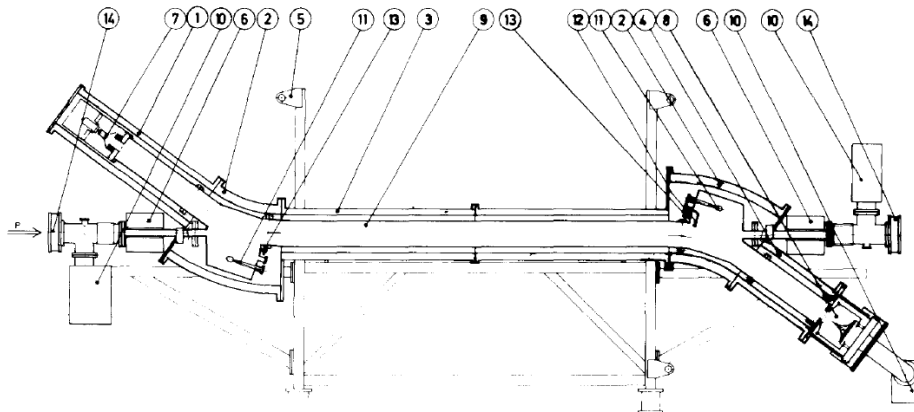
Why electron cooling at CERN?

- Improve the quality of low energy ion beams
 - *Many experiments on LEAR and AD were/are not possible without electron cooling*
 - *Used to cool (anti)protons, H, oxygen, argon, xenon and lead ions*
- Increase the duty cycle of the machine
 - *At low energies electron cooling is faster than stochastic cooling*
- LHC and North Area request a variety of ions
 - *Injection scheme requires fast cooling and stacking*

The ICE (Initial Cooling Experiment) Age



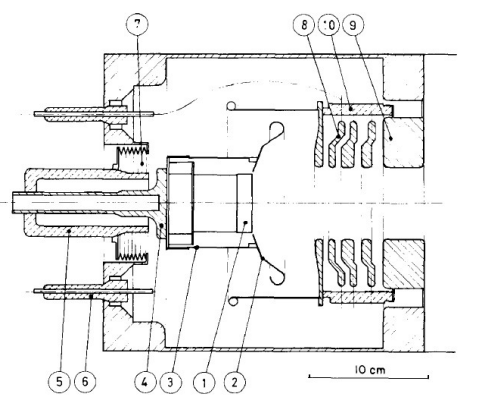
- 74.38 m proton storage ring
- 2.1 to 0.3 GeV/c
- Experimental ring to test the principle of beam cooling : stochastic & electron
- Operation close to transition
 - Pole face windings to change the tune
- 2×10^8 protons per pulse from PS
- Average vacuum pressure 2×10^{-9} Torr



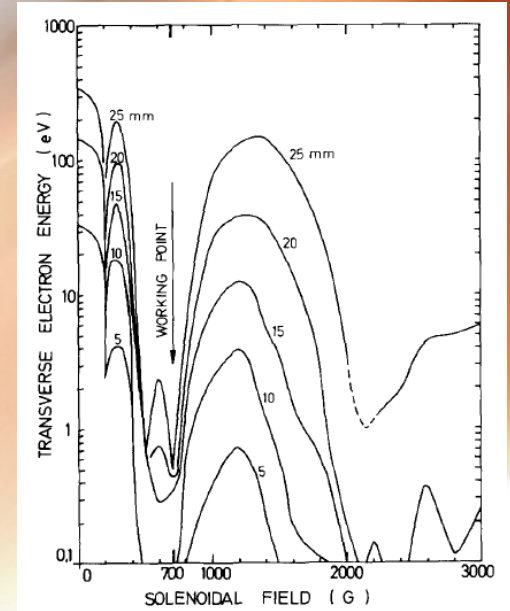
- 1 GUN SOLENOID
- 2 TOROID
- 3 CENTRAL SOLENOIDS
- 4 COLLECTOR SOLENOID
- 5 SUPPORTING FRAME
- 6 CORRECTION MAGNET
- 7 ELECTRON GUN CATHODE
- 8 COLLECTOR
- 9 STAINLESS ST. VACUUM CHAMBER
- 10 VACUUM PUMP (SPUTTER-ION)
- 11 VACUUM PUMP (Ti-SUBLIMATION)
- 12 SYNCHROTRON RADIATION ANTENNA
- 13 VIEWING PORT
- 14 SECTOR VALVE

	Design	Operational
Cathode voltage	-60 kV	-26 kV
Cathode diameter	5.08 cm	
Electron current	8.3 A	1.3 A
Cooling length	3 m	
Magnetic field	700 G	500 G

- 1 CATHODE
- 2 PIERCE SHIELD
- 3 HEAT SINK
- 4 GAS COOLED BASE
- 5 CATHODE FEEDTHROUGH
- 6 ANODE FEEDTHROUGH
- 7 BELLOWS
- 8 ANODES
- 9 ANODE
- 10 ANODE SUPPORT
- W Ta
- Mo
- Cu
- Al₂O₃
- Al₂O₃
- s.st.
- Ti
- Cu
- Al₂O₃



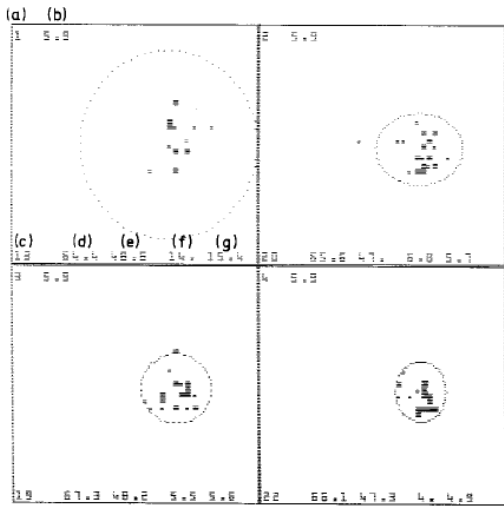
- 5 cm cathode surrounded by a Pierce shield
- Five iris shaped electrodes set on increasing potentials
- Four operational modes :
 - full perveance
 - half perveance
 - quarter perveance
 - temperature limited
- Resonant optics



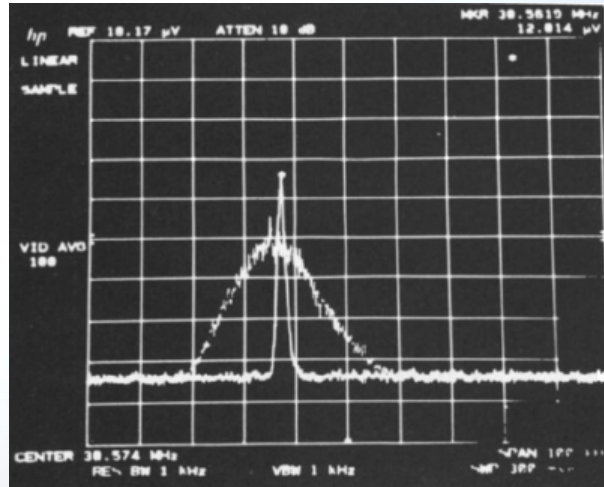
Cooling experiments

- Transverse cooling
- Longitudinal frictional force
- Equilibrium momentum spread

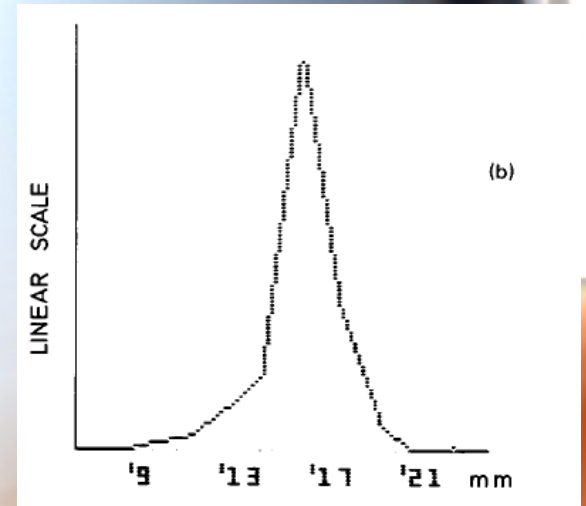
- To measure the cooled beam diameters or angular divergences, three methods were used:
 - neutral beam profile
 - beam scraper
 - horizontal ionisation beam profile monitor
- Schottky signal used for the longitudinal measurements



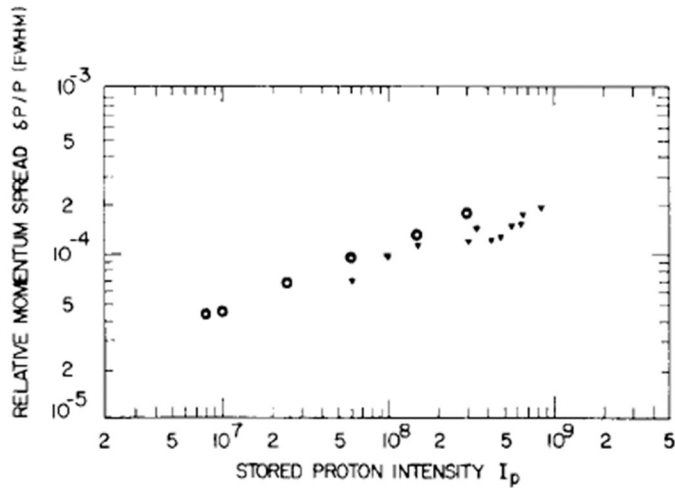
Cross-sections of neutral atom beam as seen by the two-dimensional MWPC



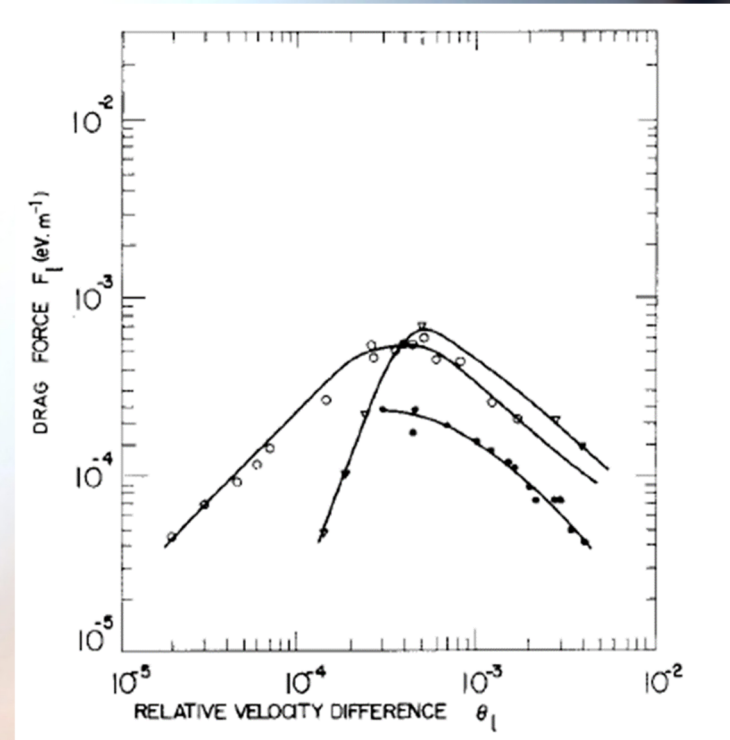
Schottky noise, taken at the beginning and end of the cooling process



Profile observed on the horizontal IPM



Equilibrium momentum spread of 45 MeV protons versus intensity. (o) temperature limited T/2 electron beam (590 mA). (∇) space charge limited P/2 electron beam (1250 mA).



The momentum cooling force, for small betatron amplitudes, was measured separately by first cooling the beam and then suddenly increasing the gun voltage and observing the subsequent acceleration of protons.

By voltage increases in the range 2-300 V fractional relative velocities in the range 5×10^{-5} to 6×10^{-3} were created. The proton acceleration was observed as a change of revolution frequency, with the longitudinal pickup

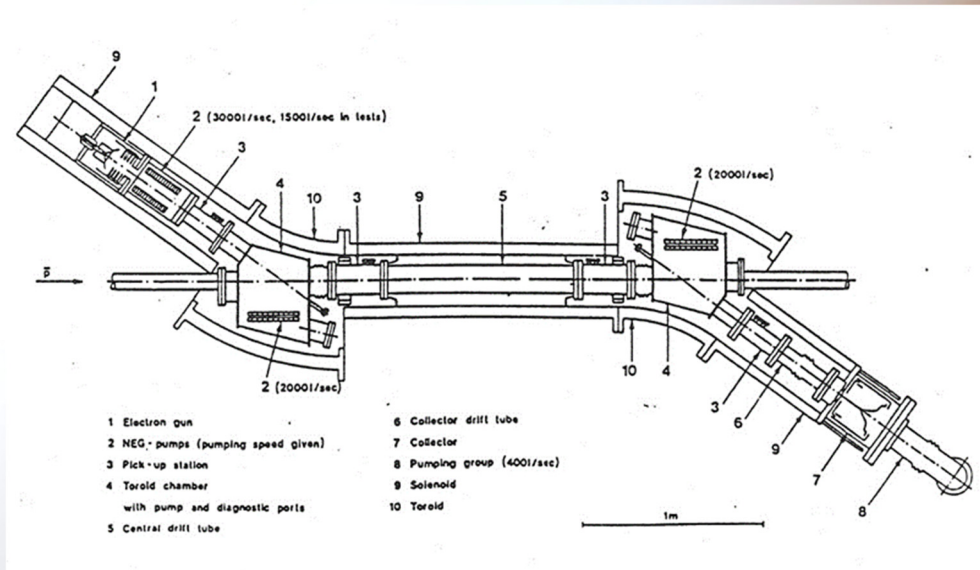
King LEAR (Low Energy Antiproton Ring)



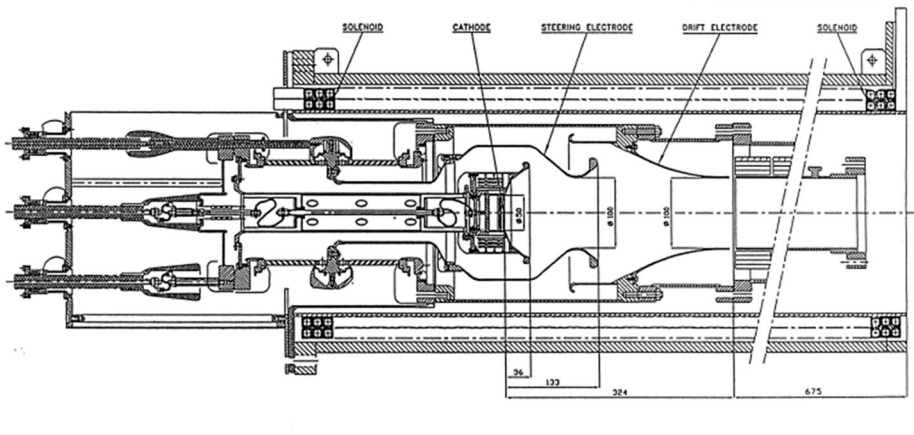
Momentum (energy) range	0.1 - 2 GeV/c (5.3 MeV – 1.3 GeV)
Circumference	78.54 m
Focussing structure	4 superperiods, separated function BoDFOFDoB
Betatron wave numbers	$Q_h = 2.3, Q_v = 2.7$
Momentum compaction	$\gamma_{tr}^{-2} = -0.048$
Maximum acceptances	$\epsilon_h = 240 \pi \text{ mm mrad}, \epsilon_v = 48 \pi \text{ mm mrad}$
RF system frequency range	0.4 – 3.5 MHz
Design pressure	$10^{-11} - 10^{-12} \text{ Torr}$

The required static vacuum level of less than 10^{-11} torr meant that the cooler needed a major upgrade of its vacuum system.

- best obtainable vacuum was in the order of 10^{-10} torr on ICE
- the complete vacuum envelope was re-designed and built using high quality AISI 316LN stainless steel
- designed to be bakeable at 300°C in situ (permanently installed jackets)
- use of NEG (non evaporable getter) strips



- Extensive studies with anti(protons), H^- , oxygen and lead ions
 - First cooling/stacking of ions
 - Instabilities – development of a damper
 - Influence of lattice parameters on beam cooling
 - Electron beam neutralisation
 - Recombination of ions
- New electron collector for reliable operation with full perveance gun
- New electron gun allowing the online control of the electron beam intensity
- Electron beam energy feedback system



Adiabatic optics
 Fixed magnetic field of 600 G (easier for operation)
 5 cm Cathode
 «steering» electrode to give the desired current
 Anode (drift) at ground potential

Oxygen ion cooling and accumulation in LEAR

11.4 MeV/nucleon

4×10^8 charges per Linac pulse

On average 8×10^9 charges accumulated (max 13×10^9)

Damper needed to fight instabilities

Accumulation scheme based on H1-H2 bunching with electron cooling and injection into empty bucket

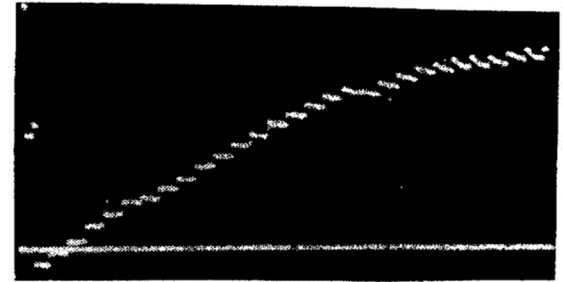
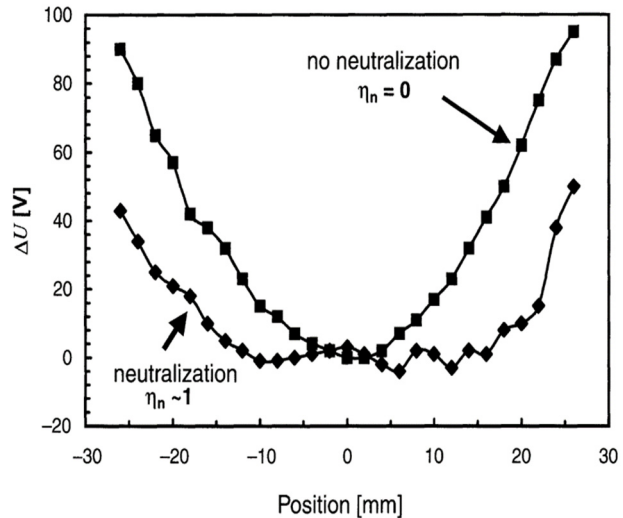
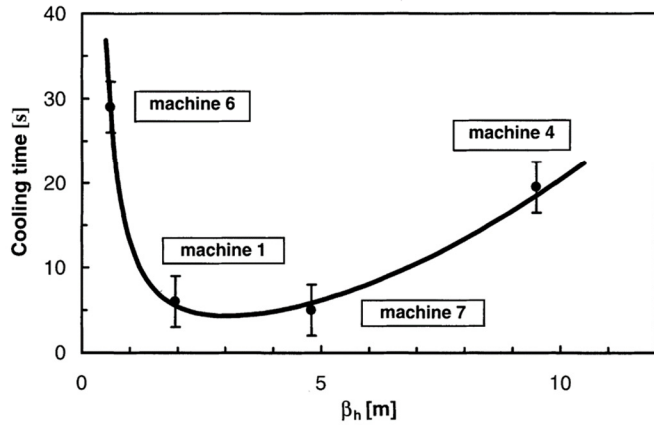


Figure 1: Current transformer reading during injection sequence. The repetition rate has been set to 7.2 seconds. Saturation occurs when the losses are of the same magnitude as the injected batch.

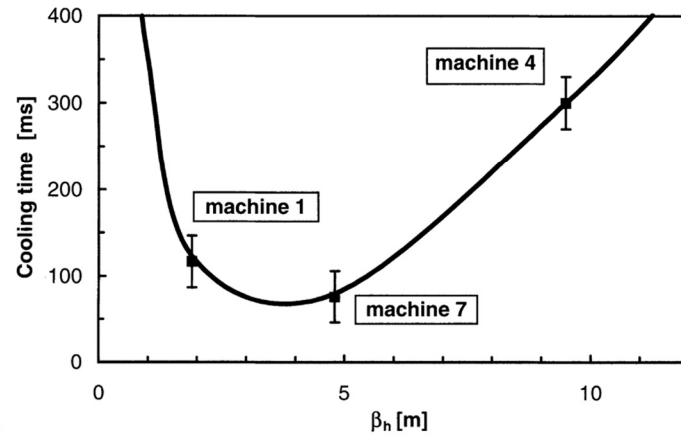
Using the circulating ion beam as a probe it was possible to measure the radial distribution of the electron beam potential. When neutralisation is switched on, the potential is constant in the central part of the beam and increases abruptly on the edges. The radius over which the potential is constant depends on the degree of neutralisation. Therefore the flatter the distribution, the greater the neutralisation coefficient.

TABLE II Lattice functions for the optical settings of LEAR used in the experiments

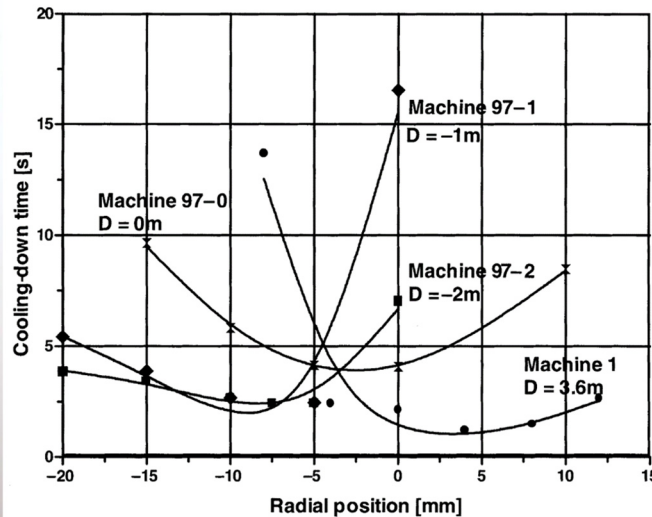
		<i>Machines used up to 1996</i> (Machine no.)				<i>Machines used in 1997</i> (Machine no.)		
		1	4	6	7	97-0	97-1	97-2
Twiss parameters at injection septum	β_H [m]	1.9	9.5	0.65	4.8	3.7	3.0	2.2
	β_V [m]	6.4	10.5	5.5	5.0	6.5	6.6	6.3
	D [m]	3.6	0	0	5.0	10	9.9	9.5
Twiss parameters at electron cooler	β_H [m]	1.9	9.5	0.65	4.8	5.0	5.0	5.0
	β_V [m]	6.4	10.5	5.5	5.0	5.0	5.0	5.0
	D [m]	3.6	0	0	5.0	0	-1.0	-2.0
Twiss parameters maximal values	β_H [m]	11.2	13.6	28.7	16.0	20.5	21.6	25
	β_V [m]	22.7	21.8	26.9	25.2	20.2	20.9	21.5
	D [m]	3.6	9.9	10.2	5.1	10	10.1	10
Working point	Q_H	2.31	1.62	2.76	2.55	1.59	1.59	1.59
	Q_V	2.62	2.42	2.72	2.70	2.57	2.57	2.57
Transition	γ_{tr}^2	-39	8.1	8.1	-28	8.1	18	-33



Cooling down time for protons at 50 MeV. The electron current was 1.2A and the cooling length 1.5 m. The measured time is the time needed to cool about 2×10^9 from a horizontal emittance of 40π mm mrad down to 4π mm mrad.

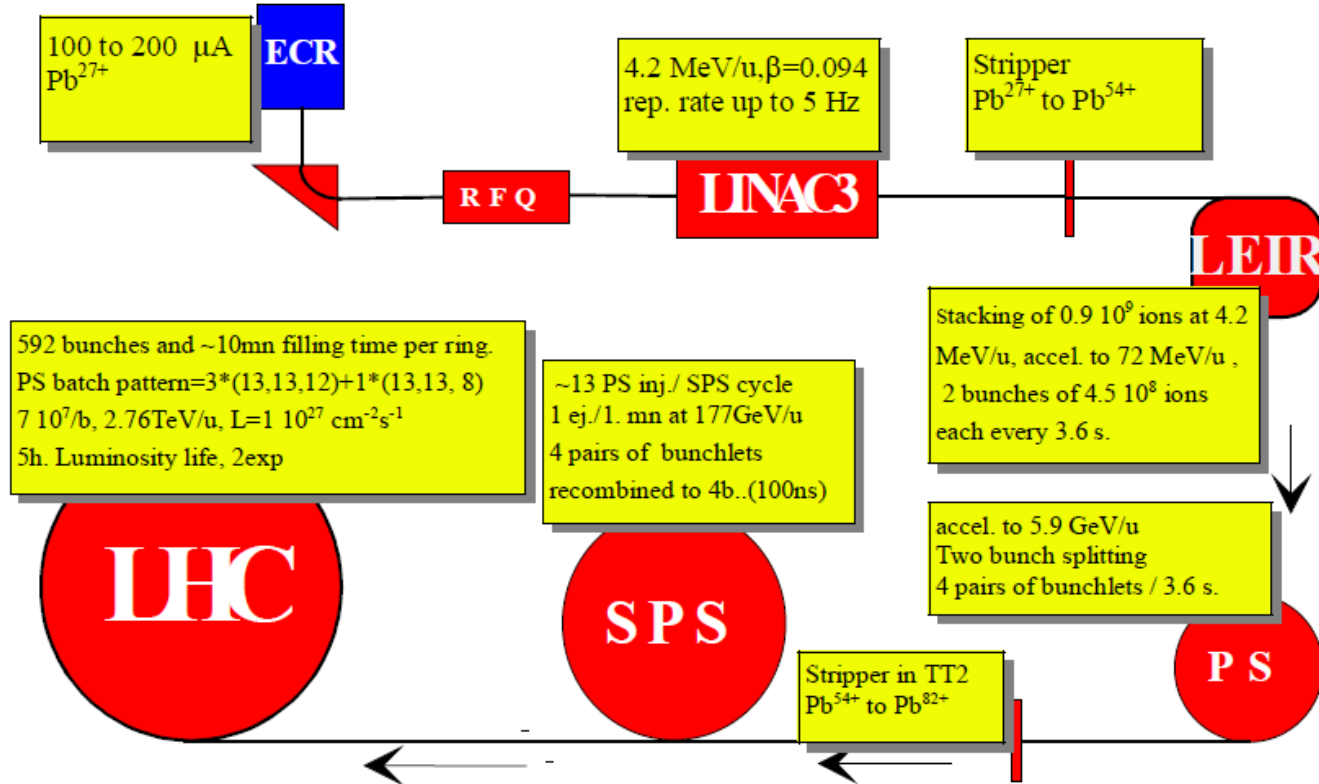


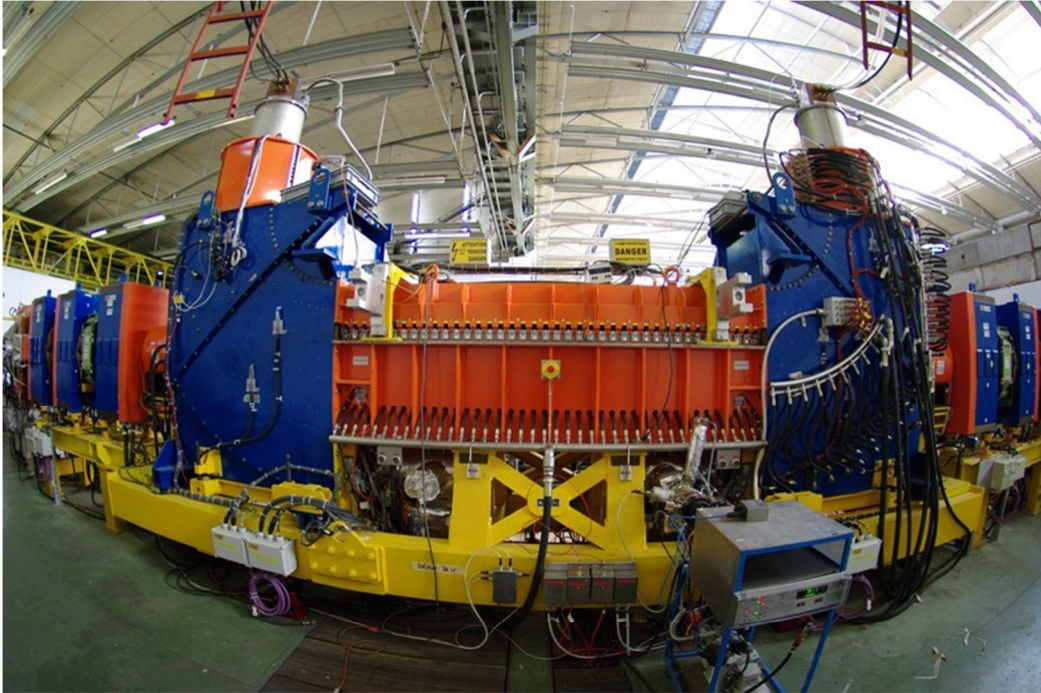
Cooling-down time for Pb^{54+} ions at 4.2 MeV/nucleon. The electron current was 350 mA and the cooling length 1.5 m.



Cooling-down time for 50 MeV protons as a function of the horizontal offset between proton and electron beam for machine 1 and machines 97-0, 97-1 and 97-2. The electron current in this measurement series was 1.1 A and the cooling length was 3 m.

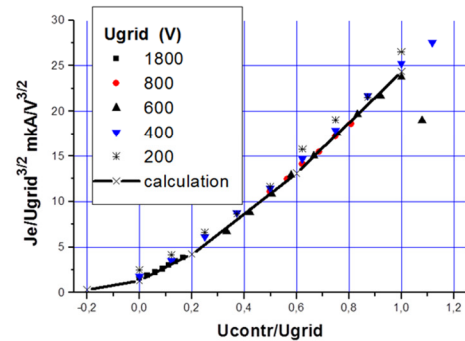
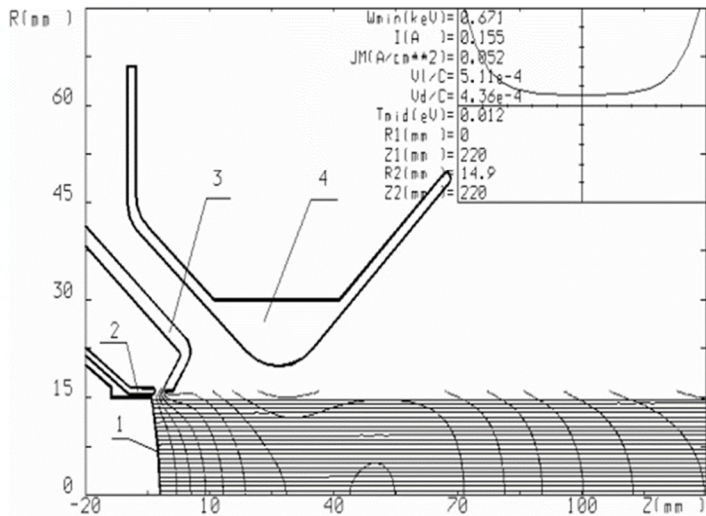
Low Energy Ion Ring



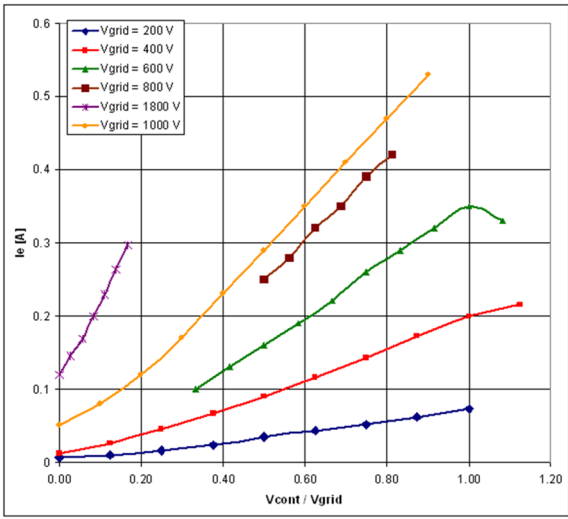
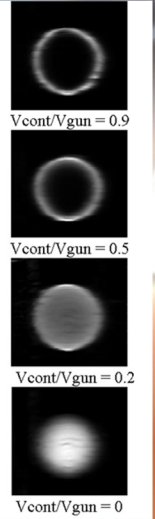


High perverance gun
Beam expansion
Electrostatic bend
Pancake structure of magnets
NEG coated vacuum chambers
NEG strips in gun/collector regions
Static vacuum pressure 4×10^{-12} Torr

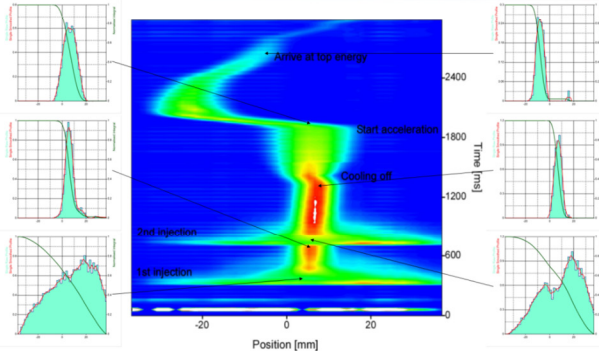
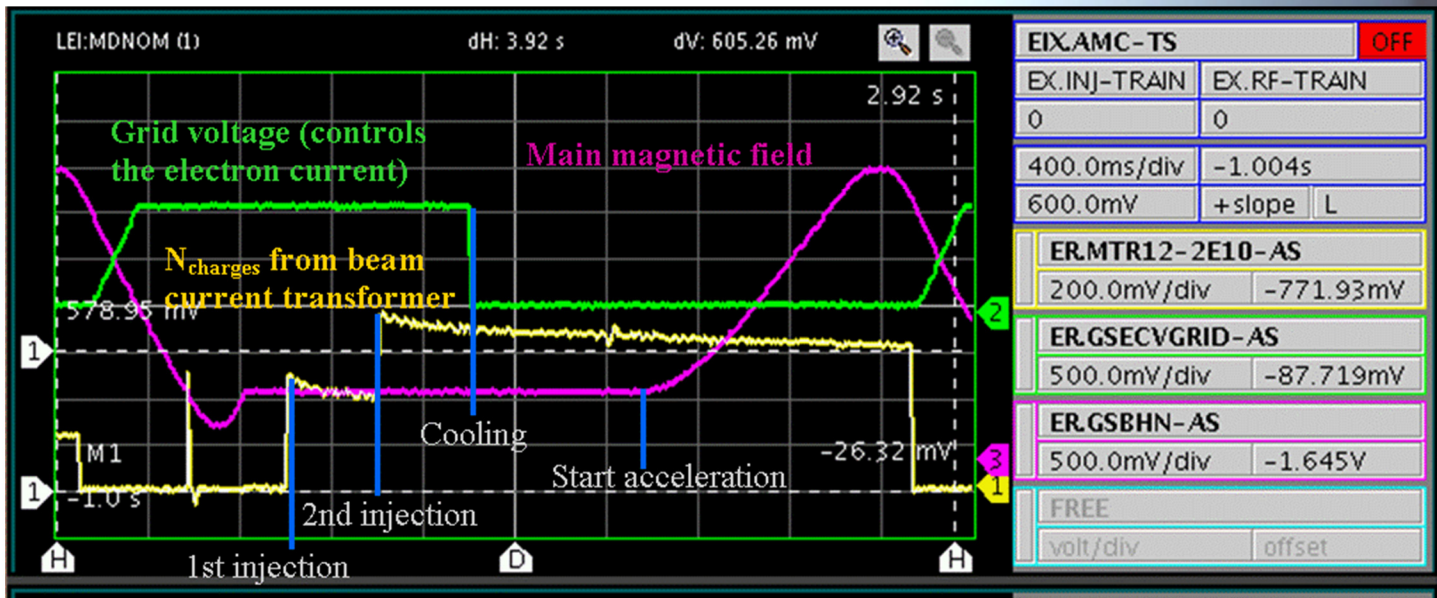
E_e up to 6.5 keV
 $I_e = 600$ mA
 $k = 3$, $r = 14$ to 25mm
 B (in cooling section) = 750 G



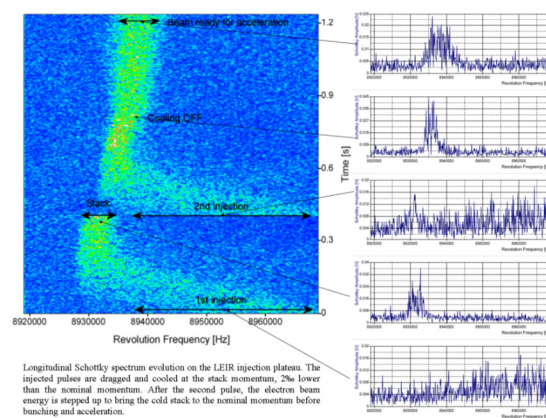
Electron beam current normalized on the grid voltage as a function of V_{contr}/V_{grid} for $E_e = 2.5 \text{ keV}$. The solid line is calculation of electron gun SuperSam code after fitting the position of the gun electrodes.



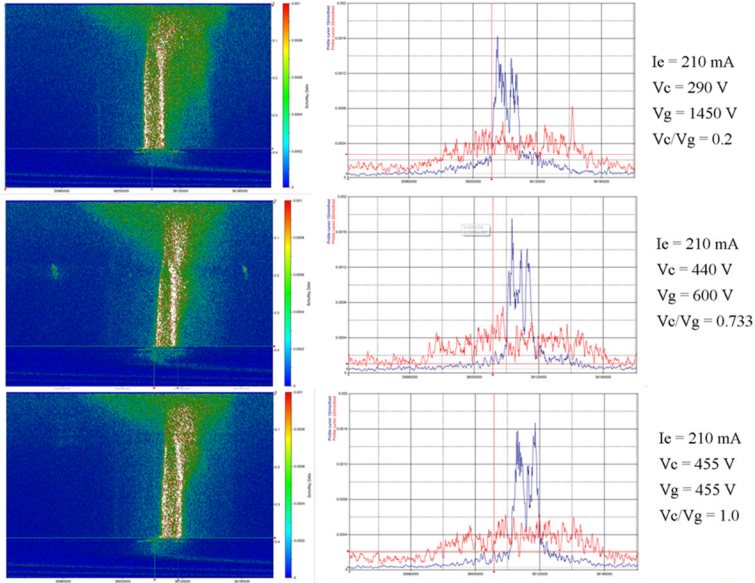
1. 14mm convex cathode
2. Control electrode (modifies density distribution and intensity)
3. Pierce electrode
4. Grid electrode (fixes the intensity)



Horizontal beam profile evolution during a complete LEIR cycle measured on the ionisation profile monitor. Two LINAC pulses are cooled-stacked at 4.2 MeV/n in 800 ns, then the beam is bunched and accelerated to 72 MeV/n for transfer to the next machine in the chain, the PS. The measured emittance at extraction is typically 0.4 μm .

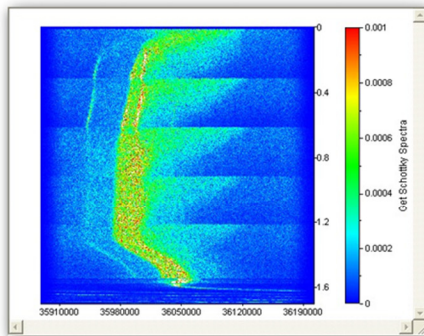


Longitudinal Schottky spectrum evolution on the LEIR injection platform. The injected pulses are dragged and cooled at the stack momentum, 2% lower than the nominal momentum. After the second pulse, the electron beam energy is stepped up to bring the cold stack to the nominal momentum before bunching and acceleration.

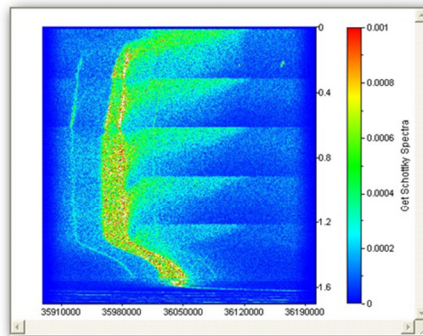


Hollow electron beam gives best results when cooling at fixed energy (i.e. one injection)

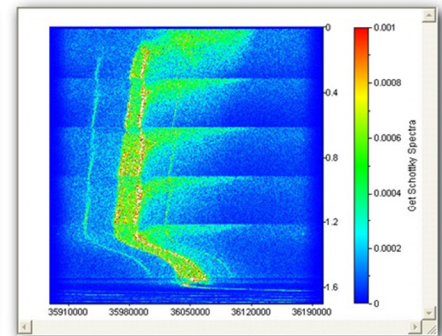
For stacking, a flat electron beam distribution gives the fastest cooling rates



$I_e = 291 \text{ mA}, V_c/V_g = 0.94$



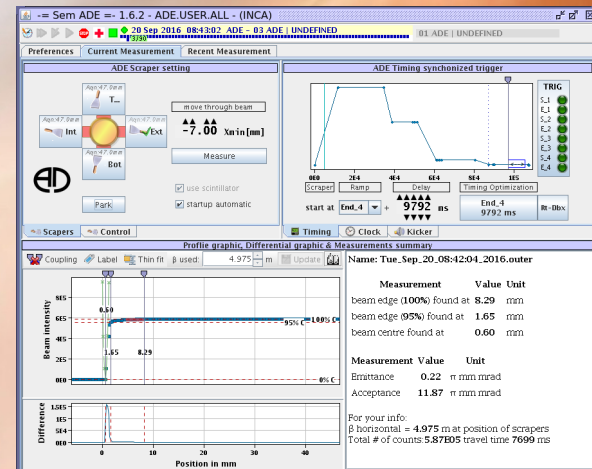
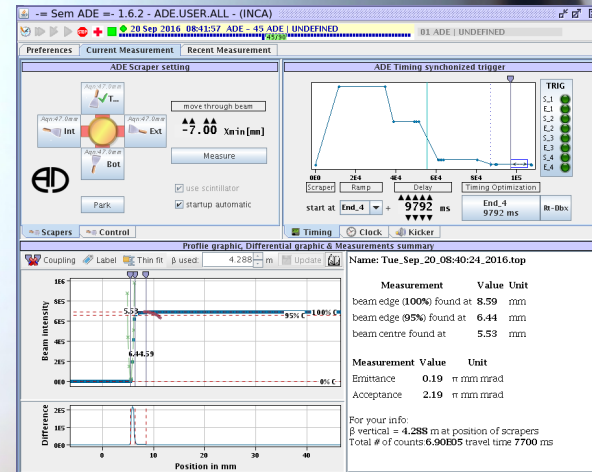
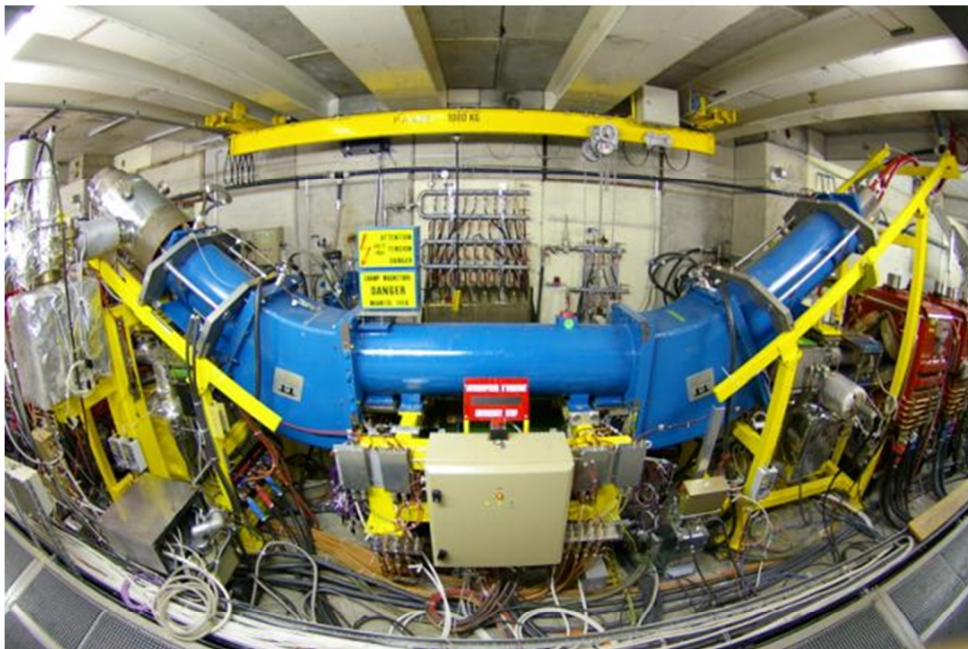
$I_e = 297 \text{ mA}, V_c/V_g = 0.5$



$I_e = 294 \text{ mA}, V_c/V_g = 0.197$

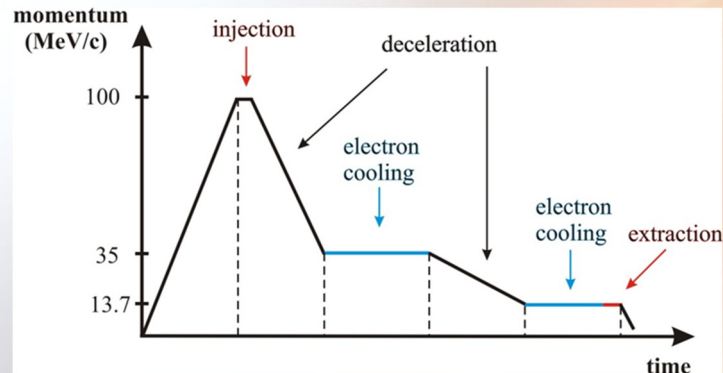
Antiproton Decelerator

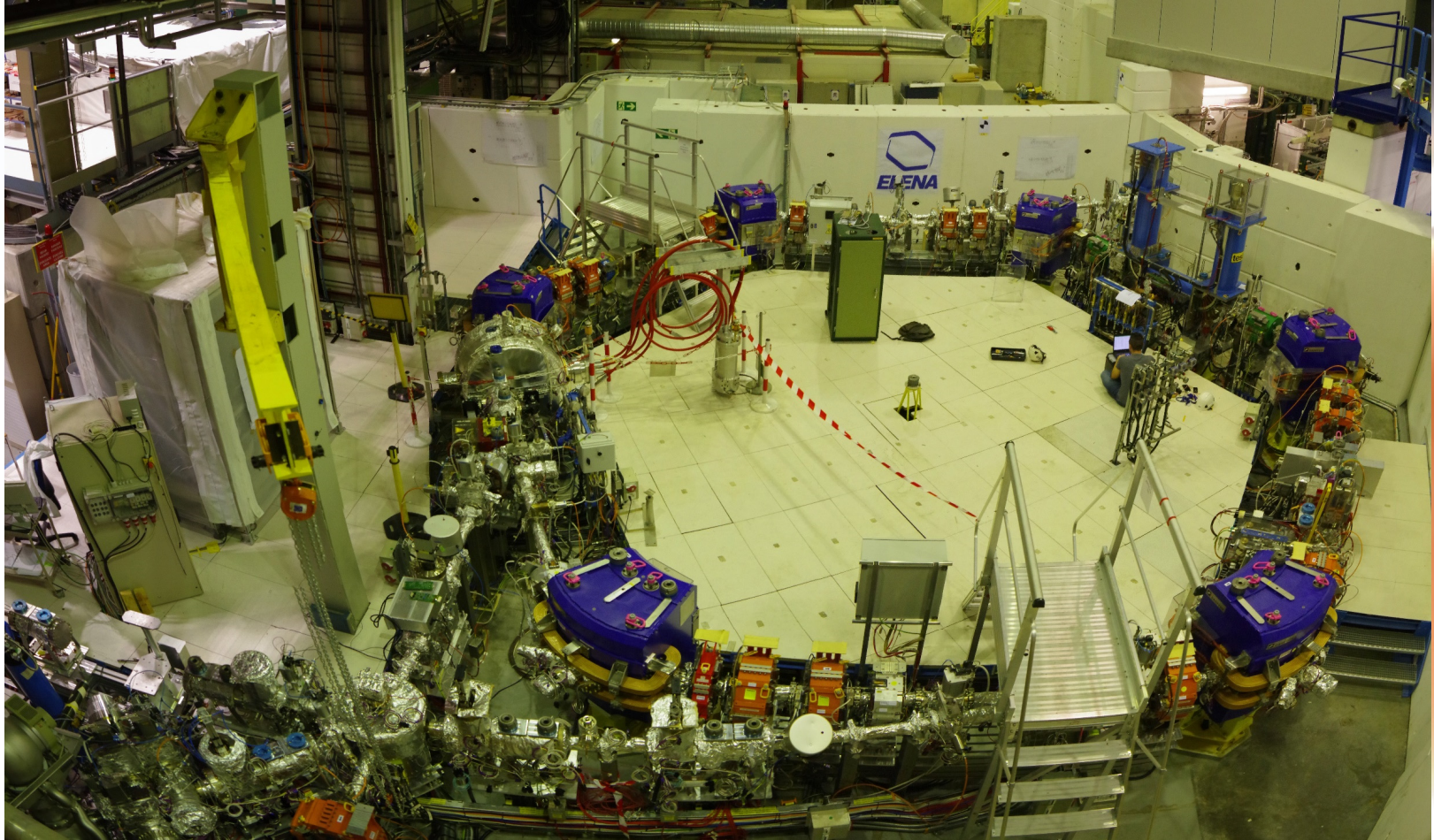
Circumference	182	m
Production beam	$1.5 \cdot 10^{13}$	Protons/cycle
Injected beam	$4 \cdot 10^7$	Pbars/cycle
Beam momenta max-min	3.57-0.1	GeV/c
Momenta for beam cooling		
• Stochastic	3.57 and 2.0	GeV/c
• Electron	0.3 and 0.1	GeV/c
Transverse emittances h/v	200 – 1	$\pi \cdot \text{mm} \cdot \text{mrad}$
Momentum spread	$6 \cdot 10^{-2} - 1 \cdot 10^{-4}$	dp/p
Vacuum pressure, average	$4 \cdot 10^{-10}$	Torr
Cycle length	<100	seconds
Deceleration efficiency	85	%



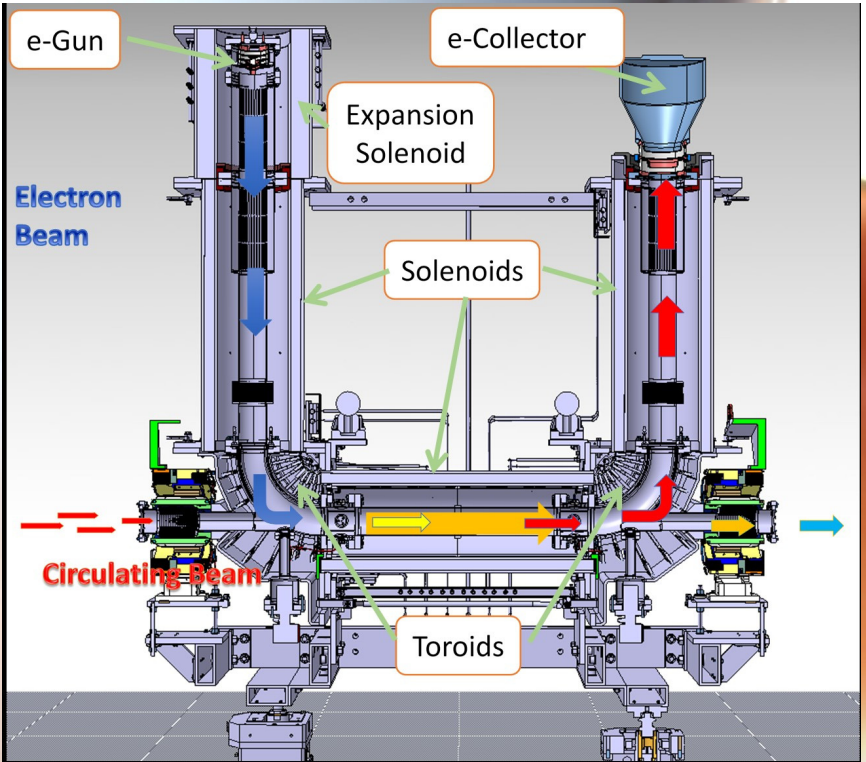
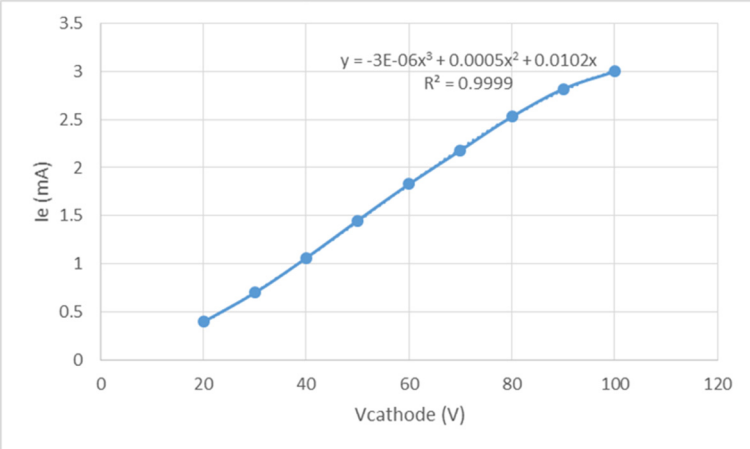
ELENA

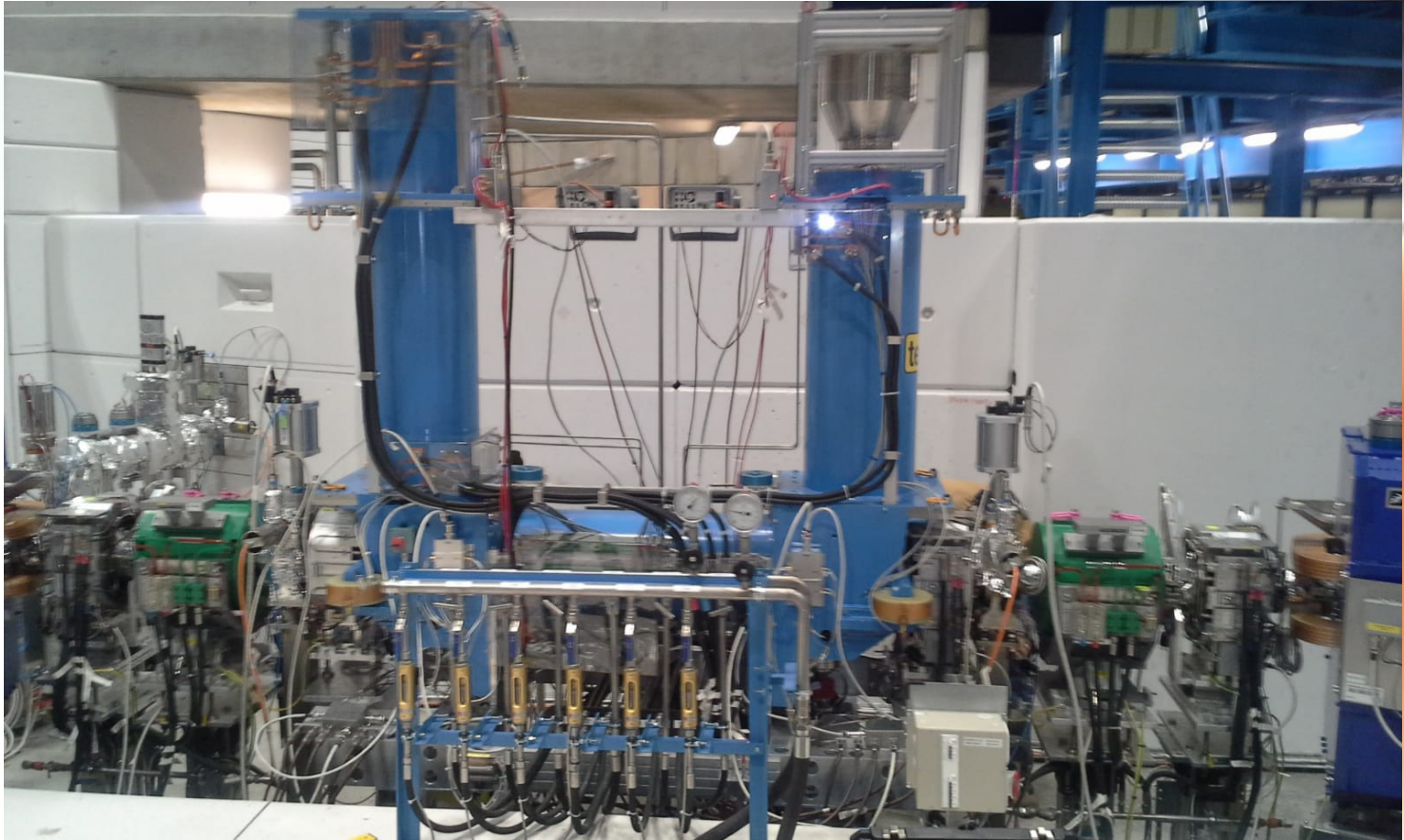
- Small post-decelerator employing electron cooling for efficient deceleration down to 100keV kinetic energy.
 - Injection of a bunched beam followed by deceleration
 - Beam cooling at intermediate momentum to counteract beam emittances and momentum spread blow up
 - Deceleration down to extraction energy, beam cooling, bunching at harmonic $h=4$, then compression to provide required bunch length and fast extraction
 - The final goal is delivering to experiments beam 1.3m long with $1\sigma \sim 1\text{mm}$





Momentum (MeV/c)	35	13.7
β	0.037	0.015
Electron beam energy (eV)	355	55
Electron current (mA)	5	1
B_{gun} (G)		1000
B_{drift} (G)		100
Expansion factor		10
Cathode radius (mm)		8
Electron beam radius (mm)		25
Flange-to-flange length (mm)		2330
Drift solenoid length (mm)		1000





Summary

Electron cooling has played a pivotal role in the success of the low energy physics program at CERN for nearly 40 years. The first electron cooler has seen two reincarnations and is still used today to provide cold antiproton beams to the AD experiments. The heavy ion program for the LHC and the fixed target experiments would not be possible without the LEIR electron cooler which accumulates and cools a variety of ions and is central in the whole injection chain. The future looks bright for electron cooling at CERN with a new low energy cooler being commissioned on ELENA and a new cooler foreseen for the AD such that the original ICE cooler can finally retire after so many years of excellent performance